

Outbursts at Comet Tempel 1

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Abstract

In the weeks leading up to closest approach with comet Tempel 1, Deep Impact observed 12 outbursts with its visual imagers. These outbursts varied in size, with the largest ejecting on the order of 10^6 kilograms of material. These outbursts are directional and dissipate on hours long timescales. One outburst on 2 Jul 2005 was detected with Deep Impact's infrared spectrometer, HRI-IR, with an acceptable signal to noise ratio. Data were collected 0.5 hours before and 1.5 hours after the onset of the outburst. All Deep Impact data are available in the PDS.

The goal of this study is to determine the abundances and distributions of water vapor, CO₂, and organics in the pre and post outburst environments using HRI-IR data. This information will then be used to help infer the cause of the natural outbursts and will be compared to what is known about other comets. This work will be done under the supervision and guidance of Dr. Lori Feaga and Dr. Michael A'Hearn at the University of Maryland.

Introduction

On July 4th 2005, Deep Impact encountered Comet Tempel 1. NASA's Deep Impact mission consisted of two separate spacecraft, a flyby and an impactor, that separated roughly one day before closest approach. The flyby spacecraft, hereafter DI, carried three scientific instruments; a medium and a high resolution visible imager, MRI and HRI-Vis, respectively, as well as an infrared spectrometer, HRI-IR. These instruments took data frequently in the weeks leading up to closest approach. The impactor spacecraft then collided with

Tempel 1 while the instruments onboard the flyby spacecraft looked on. All of these data are archived and available in the PDS.

Photometry from MRI and HRI-Vis were used to determine that the rate of rotation of the nucleus is ~ 40.8 hours (A'Hearn et al., 2005). As the nucleus rotates, the brightness of the coma fluctuates as a result of changing rates of dust production (Farnham et al., 2007). Dust is dragged off of the nucleus by the sublimation of ices, mainly CO_2 , and results in the creation of jet type activity. Though CO_2 is the volatile that is most responsible for jet type activity, water is the most common volatile in comets and tends to be outgassed from the areas surrounding the sub-solar point, which is where the nucleus is hottest (Feaga et al., 2007). Tempel 1 outgasses CO_2 at a rate that is $\sim 7\%$ that of water by number of molecules, which is typical for a Jupiter Family Comet (Feaga et al., 2007). After the impact, the CO_2 to water ratio did not change significantly (), though there was a large increase in organics (A'Hearn et al., 2005).

In addition to periodic features in the coma lightcurve, there are also sporadic spikes in brightness (A'Hearn et al., 2005). These rapid and irregularly timed increases in activity are referred to as “mini-outbursts.” Tempel 1 experiences a mini-outburst roughly once every three days (Farnham et al., 2007) and ejects on the order of 10^6 kg of material for the largest mini-outbursts (Belton et al., 2008). It has been hypothesized that small pits with scales of tens of meters on Tempel 1's surface are the result of these frequent outbursts (Belton et al., 2008). The number of observed pits on the surface is roughly 380, which proves to be many more than should be created by impacts over Tempel 1's lifetime (Belton et al., 2012).

Outbursts at Tempel 1 were primarily observed by DIF, with one outburst being observed by the Hubble Space Telescope (Feldman et al., 2007) and Calar Alto Observatory (Lara et al., 2006) as well. Other comets exhibit outburst type behavior as well; however, these events can range greatly in magnitude and in the most extreme cases, can even result in or from the breakup of the comet (Hughes, 1990). Well known examples include a large outbursts at Comet Holmes in 2007 (Sekanina, 2008) and frequent outbursts at Comet Swassmann–Wachmann 1 ().

Large outbursts are sometimes associated with splitting events, such as in the case of Swassmann–Wachmann 3, but both splitting events and large outbursts can occur independent of each other (Boehnhardt, 2004).

Though outbursts appear to be common to many comets, little is known about what is causing them. The objective of this research will be to determine the driving volatile(s) behind the mini-outbursts at Tempel 1 and to infer the physical cause of the mini-outbursts.

Data & Methods

In order to determine the driving volatile(s) behind the outburst, data from DIF's infrared spectrometer will be analyzed. HRI-IR is a long-slit spectrometer and operates between 1.05 and 4.85 μm . HRI-IR's mercury cadmium telluride detector measures 1024 pixels in the wavelength direction and 512 pixels in the spatial direction. The middle third of the detector is covered by an anti-saturation filter (ASF) to prevent the nucleus from saturating the detector, which would otherwise make that data unusable (Hampton et al., 2005).

To gather spatial data, DIF would conduct a spectral scan where the entire spacecraft rotates perpendicularly to the slit at a rate of one slit width, 10 μrad , per exposure time while the spectrometer takes data. The result is a spectral cube that can be constructed with two spatial axes and one wavelength axis. Spectral scans were conducted regularly while DIF was approaching Tempel 1.

Before the raw data can be analyzed it must first be calibrated to remove systematic error, account for detector sensitivity, and convert to actual radiance units. The calibration pipeline begins with decompressing the data if necessary. Next, linearity coefficients are applied to remove time and signal dependence of a pixel's readout. The next step in the pipeline is to remove the dark signal. To do this, an in-scene dark (ISD) will be created by taking an average of the last five frames of the scan, where there is generally no signal from the comet. After the ISD is subtracted, the data is divided by a flat field to account for pixel to pixel variation and the transmission profile of the ASF is removed. Finally, wavelength

values are assigned to each pixel. This calibration pipeline is based on a quadrant by quadrant analysis rather than a pixel by pixel analysis.

Once the data are calibrated, a continuum must be modeled then removed. Each spectrum has a unique continuum that is dominated by reflected light from the sun at shorter wavelengths and by blackbody radiation from dust grains and the nucleus at longer wavelengths. At the present time, each continuum must be modeled by hand by varying the spectral slope of the reflected light as well as the temperature of the dust. These two components are also accompanied by their own scaling factors.

After the continuum is removed from each spectrum, emission and absorption bands are left to analyze. Once an emission band is attributed to a particular substance and a fluorescence efficiency is assumed, one can calculate the number of molecules of that substance in the field of view by integrating over that emission band, converting the resulting radiance value to a flux, and using **equation 1**:

$$1) \quad \# \text{ of molecules} = \text{flux} * 4\pi * r^2 * d^2 * \frac{\lambda}{g\text{-factor} * h * c}$$

where r is the distance of the comet to the Sun in AU, d is the spacecraft to comet distance, lambda is the central wavelength of the emission band, and g-factor is the fluorescence efficiency. All units are CGS unless specified otherwise.

Previous Work

Previously, work has been done regarding the nature of the outbursts at Tempel 1 (Farnham et al., 2007), (McLaughlin, 2013). Thus far, only two of the twelve observed outbursts show enough signal within the HRI-IR spectral data to be worth analyzing. These outbursts occurred on 22 Jun 2005 and 2 Jul 2005 and will be referred to as June and July, respectively. Both of these outbursts were classified as “large” by Farnham et al. (2007).

At the current stage, a study of the radial distribution of water vapor and CO₂ has begun using data that brackets the July 2nd outburst with the goal of investigating any differences, if any, between the pre and post outburst coma. A

radial profile for what is most likely H_2CO was created from data taken post-outburst, but not before as its emission band was not detectable with any confidence in those data. These “radial profiles” are graphs of abundance vs. square aperture size and should be linear for a standard $1/r$ distribution. Aperture sizes ranging from 3 by 3 spatial pixels to 27 by 27 spatial pixels were analyzed. These radial profiles show evidence of a large increase in CO_2 after the outburst of about a factor of two. They also show a roughly 10% increase in water.

Interestingly, the radial profile for H_2CO , which was only present in large enough quantities to be detected after the outburst, shows a steep increase in slope at the 15 by 15 pixel aperture, while CO_2 exhibits a similar change at the 9 by 9 pixel aperture and the pre and post outburst profiles of water vapor begin to diverge at the 5 by 5 pixel aperture. This may indicate that the outburst “turns off” at different times for different volatile species, with H_2CO production slowing first, followed by CO_2 then water vapor.

It is important to note that once the quiescent abundances of CO_2 and water are removed from the post-outburst data, the resulting CO_2 to water ratio of the material ejected by the outburst peaks at 90 %, which is a factor of nine greater than that of the ejecta cloud from the man-made impact. If a similar composition for the nucleus as the ejecta cloud is assumed, one must conclude that CO_2 is playing a part in driving the natural outburst. If something other than CO_2 was driving the outburst, the material ejected by the outburst should have a CO_2 to water ratio that is consistent with that of the ejecta cloud. The ratio of H_2CO relative to water is expected to be around 1 % for quiescent levels of activity (Bockelée-Morvan et al., 2004) and was detected in the ejecta cloud at the 1 % level (Mumma et al., 2005), but after the outburst this ratio peaks at ~25 %. Once the quiescent abundance of water is removed and this ratio is recalculated, the peak ratio is ~155 %. Though this seems very high, a detailed analysis of H_2CO in the man-made ejecta cloud must be conducted before a firm conclusion can be made, but at the moment it does appear that H_2CO may also play a role in driving the natural outbursts at Tempel 1.

Because DIF was much farther away from Tempel 1 when the June outburst occurred as compared to the July outburst, the signal to noise ratio of the data is much lower, as well as the spatial resolution of the data. For example a 3 by 3 pixel aperture at the time of the June outburst is equivalent spatially to a 38 by 38 pixel aperture at the time of the July outburst. Radial profiles have not been constructed for this data yet.

The June outburst has thus far yielded much less information than the July outburst. The June outburst also shows an increase in CO₂; however, the magnitude of this change at this point is very dependent on the continuum removal, and thus will not be quoted. There is also evidence for water ice in the coma of Tempel 1 preceding the June outburst, which would be very interesting as water ice has not been observed Tempel 1's coma to date. This evidence includes a very shallow water ice absorption band in the central pixel's spectrum and an unexpected increase in water vapor, beyond that expected for a 1/r distribution, between the 3 by 3 pixel aperture and 5 by 5 pixel aperture, which would indicate that the ice is subliming within the 5 by 5 pixel aperture. This odd distribution is not mimicked by the CO₂, which is much more consistent with a 1/r distribution. This evidence is circumstantial at present, but is certainly enough to warrant further investigation.

Future Research Goals

The main goals for this PDS intern research will be to determine the driving volatile(s) and cause of the mini-outbursts at comet Tempel 1. This will be done by conducting a detailed spectroscopic investigation of the outbursts at Tempel 1 using archived data from the PDS-SBN as well as the best calibration files available from the Deep Impact/EPOXI science team, and of course the available literature. Though only the outbursts that occurred on 22 Jun 2005 and 2 Jul 2005 have shown any signs of the outbursts occurring in the spectra taken by DIF, it may be useful in the future to investigate any of the other ten outbursts as

well, though those that occurred before 19 Jun 2005 can not be analyzed because the spectral scans acquired before this date were off target.

It will also be important to do a more detailed investigation of the man-made ejecta cloud to get a baseline comparison for what material ejected from the surface of a comet should look like. This will allow for constituents that were ejected with the outburst to be distinguished from those that are driving the outburst.

Up to this point, all continuum modeling and subtraction was done manually through guess and check, but it is necessary to do this in a more robust manner. To do this a chi squared minimization program will be developed and refined to remove the human element from the continuum removal process. This may be done by having the program determine a “best fit” continuum for a set dust temperature by varying the reflected sunlight’s scaling factor as well as the scaling factor for the Plank function, which models the blackbody spectrum of the dust. The program will then do this for a number of temperatures, picking the best continuum (i.e. the one with the lowest chi squared value) to output. A similar process will then be done for the spectral slope of the reflected continuum. Chi squared values will be determined for averages over set intervals rather than for individual data points as to reduce the effect of noise. The number of points should be at least six, given that the continua are modeled off of four parameters. These points must also not be within an area either prone to excessive noise or within an emission or absorption band, as these points will be at the zero line once the continuum is removed from the spectrum. These automated fits will be spot checked and adjusted if necessary. The process of continuum removal is important because the abundances of the molecules in the field of view will yield the most robust information about the outbursts, and will allow for numerical comparisons as opposed to more relative comparisons.

Once volatiles are identified and abundances are calculated this information will be used to help determine the driving volatile(s) and cause of the mini-outbursts at Tempel 1, which can yield important information concerning how comets evolve and change from their primordial states. This will assist in the

overarching goal of using comets as windows to the formation of the Solar-System.

Collaboration and Mentors

This research will be conducted at the University of Maryland as part of the Planetary Data System-Student Investigator program. Dr. Lori Feaga and Dr. Michael A'Hearn will be mentoring me, as well as collaborating with me, on this project. The PDS-SI program is led by Dr. Susan Hoban, who will also act as a mentor during my time as a PSD-SI.

Timeline

Start researching outbursts.....	August 2012
Preliminary results gathered.....	November 2012
Begin more thorough investigation.....	May 2013
Taken on as PDS intern.....	March 2014
Proposal rough draft.....	March 2014
Final PDS proposal done.....	July 2014
Finish analysis of July outburst.....	August 2014
Do analysis of quiescent coma/ejecta cloud for H ₂ CO	August 2014
Investigate other outbursts.....	August 2014
Have rough draft of paper done.....	August 2014
Have paper submitted for peer review.....	September 2014
Peer Review and Presentations.....	November 2014-April 2015

References